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Lewis Research Center
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SUMMARY

Experimental frequency-response techniques were used to obtain pressure and flow-perturbation data for a hollow single-tube boiler. The flow rate of the test fluid was sinusoidally varied about a mean value. Amplitudes and phase angles of the pressure and flow perturbations were measured at the boiler inlet. The boiler test section was a shell and tube heat exchanger. Freon-113 was the test fluid flowing inside the inner tube that had an inside diameter of 0.315 inch (8.0 mm) and a heated length of 36 inches (0.91 m). Hot water flowed countercurrent to the Freon flow in the annulus between the inner tube and the outer jacket. The data are presented in terms of the boiler-inlet impedance as a function of disturbance frequency. For all conditions investigated, the boiler-inlet impedance was found to have a negative real part over some frequency range. Boiler-inlet impedance was found to be a function of exit vapor quality; the magnitude of the impedance was larger at the higher qualities.

INTRODUCTION

Two-phase flow-stability problems have been encountered in the development and testing of boilers in which net vapor generation occurs. Boiler instabilities, which have been detected by many investigators (refs. 1 and 2), are complex in nature and very difficult to analyze. An important class of instabilities (manifested by unsteady flow in the system) are those which result from the dynamic characteristics of the boiler and other loop components.

An insight into the dynamic characteristics of the boiler, and therefore boiler stability on a macroscopic scale, can be obtained by use of frequency-response techniques. The objective of the work reported herein was to obtain frequency-response data for a single-tube forced-flow boiler over a range of heat fluxes and exit vapor qualities. Techniques and equipment similar to those used successfully in studies of the dynamics of liquid-filled systems (ref. 3) were employed to measure the dynamic impedance of the boiler inlet.

DEFINITION AND MEASUREMENT OF BOILER-INLET IMPEDANCE

The use of frequency-response methods is based on the hypothesis that, for small amplitude disturbances, the boiler can be treated as a linear element. For a linear boiler with constant pressure at the exit, the complex ratio (amplitude ratio and phase difference) of boiler-inlet pressure perturbation to inlet flow perturbation for sinusoidal perturbations is a function of frequency and boiler parameters only. This complex ratio of pressure perturbation to flow perturbation is analogous to the input impedance of a four-terminal electrical network with the output shorted. Thus, the complex ratio of pressure perturbation at the boiler inlet to flow perturbation at the boiler inlet with constant pressure at the boiler exit is referred to as the boiler-inlet impedance.

The boiler-inlet impedance was obtained experimentally by oscillating the open area of a valve in the feed system about a mean area and measuring the pressure and flow at the boiler inlet. The pressure and flow signals were analyzed by a frequency-response analyzer. This analyzer computed the amplitude and phase (relative to a sinusoidal reference oscillator) of the sinusoidal content of the pressure and flow signals at the frequency of the reference oscillator. Since the analyzer required that the pressure and flow signals have a sinusoidal content at exactly the frequency of the reference oscillator, the reference oscillator was also used to drive the valve in the feed system.

APPARATUS AND PROCEDURE

Description of Test Facility

A schematic diagram of the test facility is shown in figure 1. Flow is provided in the Freon loop by a gear pump. An accumulator located downstream of the gear pump prevents flow perturbations out of the pump from traveling to the boiler. The accumulator, by acting as a quasi-constant pressure supply, permits controlled flow and pressure oscillations to be put into the boiler by an electrohydraulically controlled globe valve. The valve was located between the accumulator and the boiler. The valve open area was oscillated sinusoidally about a mean value, in response to a command oscillator, to impose oscillations on the mean flow through the valve and into the boiler.

The Freon flow through the boiler was vertically upward. A schematic drawing of the boiler is given in figure 2. The boiler was a single-tube shell and tube heat exchanger. The inner tube was copper with an inner diameter of 0.315 inch (8.0 mm) and a wall thickness of 0.030 inch (0.76 mm). The shell was a brass tube with an inner diameter of 0.620 inch (15.7 mm). The heated length was 36 inches (0.91 m). The Freon was vaporized in the boiler by hot water flowing countercurrently in the annulus between the inner and outer tubes. The boiler shell was insulated to reduce heat losses.

The Freon exhausted into a plenum tank located downstream of the boiler. The end of the boiler tube extended into the plenum tank for a distance of about 3 inches (76.2 mm) to prevent a buildup of liquid at the boiler exit. A 0.870-inch (22.1 mm) inside-diameter tube (low impedance) connected the plenum tank to a large water-cooled condenser. The connecting line was large enough so that no measurable pressure drop existed from the plenum tank to the condenser for the flow range encountered. The condenser consisted merely of a large volume tank (70 gal (0.26 m^3)) with water flowing in coiled tubing placed inside the tank. The condenser was left open to the atmosphere to maintain constant pressure at this point in the system. The water in the heating loop was heated with steam in a multitube heat exchanger and pump fed through the boiler.

Instrumentation

Instrumentation was provided to measure steady-state values of Freon flow rate, water flow rate, Freon pressure and temperatures at the inlet and exit of the boiler, and the water temperature profile in the boiler. Dynamic instrumentation was provided to measure Freon pressure and liquid Freon flow rate at the inlet of the boiler.

Steady state. - Freon and water flow rates were measured with commercial turbine flowmeters. The Freon flowmeter was located between the pump and accumulator. The water flowmeter was located between the boiler and the heat exchanger used to heat the water. Freon pressures at the boiler inlet and exit were measured with Bourdon tube pressure gages. Inlet pressure was measured 12 inches (30.48 cm) upstream of the boiler, and exit pressure was measured 6 inches (15.24 cm) downstream of the boiler. In addition, the pressure in the exit plenum tank was measured. Copper-constantan thermocouples (bare junction, 0.005-in. (0.127 mm) wires) were used to measure temperatures. The Freon temperature was measured at the boiler inlet and exit. The hot water temperature in the boiler was measured at the locations shown in figure 2.

Dynamic. - Perturbations in Freon pressure at the boiler inlet were measured with a flush mounted quartz crystal pressure transducer. Perturbations in Freon flow at the boiler inlet were measured with a turbine flowmeter. The pressure signal and the pulse output of the turbine flowmeter were sent through a first-order band-pass filter centered at the perturbation frequency. The filter averaged the pulse output of the flowmeter and filtered both the pressure signal and the averaged flowmeter signal.

The perturbation signals were analyzed by a commercially available frequency-response analyzer. This analyzer made a Fourier analysis of the perturbation signals. This analysis isolated the components of the perturbation signals at the test frequency and computed the amplitude and phase (relative to a reference oscillator) of these components.

Calibration. - The quartz crystal pressure transducer was calibrated by applying known pressures and recording the voltage output. Calibration curves for the turbine flowmeters were supplied by their manufacturers. It was assumed that the transducer and the turbine flowmeter followed their steady-state calibration curves over the range of their frequency-response limits. The nominal resonant frequency of the pressure transducers is quoted by the manufacturer to be 60 000 cps (Hz). The frequency-response limit of the turbine flowmeter was determined experimentally and found to be 4 cps (Hz). This limit was determined by comparing the measured response of pressure to flow at the inlet of an all-liquid line to the theoretical response. For a short (relative to acoustic wavelength) all-liquid line, the response of pressure to mass flow should be of the form $R + j\omega(l/A)$ (ref. 4), where R is the slope of the curve for steady-state pressure drop against mass flow, ω is the angular frequency of oscillation, l is the length of the line, and A is the cross-sectional area of the line. The frequency at which the phase shift of the measured response deviated from this form by more than 5° was taken as the upper frequency-response limit of the turbine flowmeter. The frequency-response limit of the flowmeter was obtained at mean flow rates of 325 pounds per hour (0.041 kg/sec) and 635 pounds per hour (0.080 kg/sec) and was found to be about 4 cps (Hz).

The frequency-response analyzer was checked by applying sinusoidal voltages to a simple resistance-capacitance electrical circuit. A voltage in the circuit was analyzed by the frequency-response analyzer. The measured response was compared with the calculated response and the agreement was satisfactory from 0.01 to 90 cps (Hz).

Test procedure. - The experimental program was designed to obtain the dynamic data over a range of heat fluxes and exit vapor qualities. The water flow rate was held at approximately the same value for all runs. The inlet water temperature was adjusted to three different levels and held constant over a range of Freon mean flow rates. At a given inlet water temperature, the Freon mean flow rate was varied in order to obtain different exit qualities. The inlet temperature of the Freon was held constant during each frequency-response run.

For a particular run, the general operating procedure consisted of setting the desired mean Freon flow rate, water flow rate, and water inlet temperature. After conditions had stabilized, the accumulator in the Freon loop (fig. 1) was charged with air and opened to the system. When the liquid level in the accumulator reached a constant location, the mean pressures at the boiler inlet and exit were recorded from Bourdon tube pressure gages. The pressure gages were then valved off from the system. The oscillating throttle valve (fig. 1) was then actuated. The throttle valve was operated over a frequency range from 0.04 to 4.0 cps (Hz). The amplitude of the throttle area variation was maintained constant over the entire range of frequencies for each run. In addition, the amplitude was kept small, relative to the mean open area, to reduce nonlinear effects.

At each frequency, the amplitude and phase angle (relative to the command signal) of the inlet pressure and Freon flow rate were read from the frequency-response analyzer. The amplitude ratios and phase angles were plotted as a function of frequency at the time the data were taken. This procedure allowed immediate investigation of frequency ranges where the results were rapidly changing. The Freon mean flow rate, water flow rate, and water inlet temperature were continuously monitored to ensure that the mean operating conditions remained constant. All mean flow rates and temperatures were recorded approximately every half hour.

For the steady-state pressure drop measurements, the oscillating throttle valve was not actuated and the accumulator was not open to the system. The steady-state pressures were measured at the boiler inlet and exit from the Bourdon tube pressure gages.

RESULTS

Tabulation of Data

The results of the dynamic tests are tabulated in tables I and II. (All symbols are defined in the appendix.) Table I gives the mean operating condition for each run for which dynamic measurements were made. The runs are arranged in order of increasing exit vapor quality. Exit vapor quality was calculated from a heat balance with the assumption that the measured exit pressure defined the saturation condition at the exit. The Freon exit temperature indicated that the fluid was superheated over the quality range from 12 to 63 percent. This superheating was attributed to stratification of the mixture, that is, annular flow with superheated vapor in the center. For analysis purposes, the data of table I are grouped about three nominal values of inlet water temperature (station I): 210° F (372° K), 230° F (383° K), and 250° F (394° K). The locations of the water temperature stations are shown in figure 2. Freon inlet mean pressures include the hydrostatic head. The subcooled length, or the distance required for the liquid Freon to reach saturation temperature, is included in table I.

The boiler perturbation data are tabulated in table II. The amplitude and phase angle relative to the oscillator are given for the Freon flow and boiler inlet pressure. Although both pressure and flow perturbations relative to the oscillator are dependent on the entire system, the effect of the feed system and the perturber valve cancel out of the ratio, and the resulting impedance is a function of the boiler only.

Steady-State Pressure Drop

Steady-state pressure-drop data were taken independently of and prior to the dynamic testing. The results are presented in figure 3 (open symbols) as a function of Freon flow rate for three different water inlet temperatures. The numbers next to the symbols are vapor exit qualities. The pressure drop presented in figure 3 was the drop from the boiler inlet to atmosphere. The measured pressure drop from the plenum tank to the receiver tank was zero for the range of conditions of this test. Data from table I are also included in figure 3 (solid symbols).

The shapes of the curves are similar to those reported by other investigators (ref. 1). The pressure-drop data for a water inlet temperature of 250° F (394° K) did not cover the complete flow range. The low-quality, constant, pressure-drop portion of the curve was out of the range of the facility. Further, the high-quality portion of the curve is not shown because, at qualities greater than 35 percent (flow rate less than 420 lb/hr (0.053 kg/sec)) the boiler was unstable with self-sustained inlet pressure and flow fluctuations occurring.

The pressure drop against flow curve for a water inlet temperature of 210° F (372° K) shows a region of decreasing pressure drop with increasing flow. Dynamic data taken in this negative slope region are included in the work presented herein and are discussed in later sections.

The data for water inlet temperatures of 210° F (372° K) and 230° F (383° K) terminate at maximum qualities of 63 and 47 percent, respectively. It was not possible to obtain higher qualities by decreasing Freon flow rate, since a transition to the film-boiling regime would occur in the test section. Transition to film boiling was ascertained by the nature of the water temperature profiles.

Water Temperature Profiles

Water temperatures were measured with bare-junction thermocouples with individual wire diameters of 0.005 inch (0.127 mm). The response rate of the small size thermocouple bulb immersed directly in the liquid stream was assumed to be sufficiently rapid to detect local water temperature perturbations caused by the dynamics on the Freon side of the boiler. During the acquisition of the dynamic data, water temperatures were monitored periodically on a high-speed pen recorder. No water temperature oscillations were observed.

Typical examples of water temperature profiles are shown in figure 4. As the Freon mean flow rate is decreased, a change in the shape of the profile is evident. The temperatures plotted in figure 4(a) show a somewhat linear variation in water temperature with length. The run of figure 4(b) shows a region near the water inlet (exit of the test section) as having a constant water temperature for a short distance, a region of slightly decreasing temperature, and then a sudden change in the slope of the profile occurs (transition to film boiling). The constant temperature region beyond the transition point is a region where little or no heat transfer is taking place, since, for heat transfer from the water to the Freon to occur, the water must undergo a temperature change. The location where the Freon reaches the saturation temperature corresponding to the inlet pressure is indicated by the dashed line in figure 4. The point was determined by a heat balance between the two fluids assuming no pressure drop in the subcooled portion of the boiler and thermodynamic equilibrium. Reducing the Freon flow rate even further in an attempt to increase the vapor exit quality resulted in the water temperature profile shown in figure 4(c). The water temperature undergoes little or no change from the inlet to the transition point for the set of conditions shown in figure 4(c).

Frequency-Response Results

Boiler-inlet impedance as a function of disturbance frequency is shown in figure 5 for data obtained with a nominal water inlet temperature of 210° F (372° K). The data presented in figure 5 were taken at operating points on the positive slope part of the steady-state pressure-drop - flow-rate curve of the boiler (fig. 3) for this water temperature level. The data (runs 1, 3, 4, and 5 of table II) are arranged in order of increasing exit quality.

At the lowest quality (fig. 5(a)), the amplitude ratio increases with frequency up to about 1 cps (Hz) and then decreases to go through a resonance at 1.7 cps (Hz). Essentially, a constant value of amplitude ratio was measured for this run between 2.5 and 4.0 cps (Hz). The phase angle between the inlet pressure and flow perturbation is shown to start at zero and approach -300° as the frequency increases. The scatter at the low end of the frequency range (below 0.1 cps (Hz)) is attributed to two causes: First, because the operating point was on the flat part of the steady-state pressure-drop - flow-rate curve (fig. 3), there was a low signal to noise ratio during the measurements. Second, the operating point was close to the boundary of the negative slope (negative resistance) region of the pressure-drop - flow curve.

A different character in the amplitude ratio and phase angle curves was obtained for runs 3 to 5 (figs. 5(b) to (d)). Above 0.2 cps (Hz) the general trend is to approach a linear decrease in the amplitude ratio with frequency as the quality increases. A resonant region at about 1.8 cps (Hz) is again evident for run 3 (fig. 5(b)) but is not well defined for runs 4 and 5 (figs. 5(c) and (d), respectively). At frequencies near 4 cps (Hz), the change in amplitude ratio with quality is not as pronounced as it was at low frequencies. The curves for phase angle against frequency shown in figures 5(b) to (d) are typical of situations in which a dead-time phenomenon is a contributing factor to the results, that is, an ever increasing phase angle between the two variables of interest.

The only parameters contributing to the dead-time term are believed to be the mean flow rate and the length of the subcooled region of the boiler (ref. 5).

Boiler-inlet-impedance amplitude and phase angle can be conveniently illustrated on a single figure by using polar coordinates. Faired values of amplitude and phase taken from figure 5 are plotted in this form in figure 6. The curves of figure 6 show the locus of the impedance as a function of frequency. Frequency increases in a clockwise direction. The amplitude of the impedance is the distance from the origin to the curve.

The curves of figure 6 show that the real part of the dynamic impedance of the boiler is negative (phase angles between -90° and -270°) over a considerable range of frequencies for each of the runs. For example, at an exit quality of 29 percent (fig. 6(b)) the real part of the boiler-inlet impedance is negative for frequencies between 0.2 and 0.8 cps (Hz). The existence of a negative dynamic impedance over a significant part of the frequency range of each of the data plots implies the possibility of a hydrodynamic instability occurring, particularly at high qualities, where the larger values of negative impedance occurred. For the boiler used in this study (with the same constant pressure exit condition), a feed-system-coupled hydraulic instability will occur if, at some frequency, the feed system impedance is equal to or less than the boiler impedance and 180° out of phase with the boiler impedance. For a simpler example, consider a hypothetical boiler feed system which is entirely resistive. The magnitude of the boiler impedance at 180° is then a measure of the amount of feed system dynamic resistance needed for neutral stability. For the 210° F (372° K) water inlet condition, this resistance ranges from 0.0009 pound per square inch per pound per hour (49 300 $\mathrm{N/m^2})/(\mathrm{kg/sec})$) at 12-percent exit quality to 0.0118 pound per square inch per pound per hour (645 600 $(\mathrm{N/m^2})/(\mathrm{kg/sec})$), at an exit quality of 63 percent. Feed system resistances larger than these values would permit stable operation in which no system flow and pressure oscillations could occur at these operating conditions.

The experimental frequency-response data of this report were taken with sufficient feed system impedance so that instabilities did not occur during the frequency-response runs. The dynamic resistance of the hydraulic servothrottle valve was the principal stabilizing element of the feed system.

As mentioned previously, the data of figures 5 and 6 were taken in the operating region in which the boiler had a positive steady-state resistance. In addition, a set of frequency-response data was taken in the steady-state negative resistance region of the boiler. The steady-state negative resistance region (see fig. 3) is that portion of the characteristic curve where a decrease in pressure drop occurs with an increase in flow rate. The results of these frequency-response tests (run 2 in table II) are shown in figure 7 and in polar form in figure 8. As would be predicted from the steady-state data, figures 7 and 8 show that the phase angle of the boiler-inlet impedance starts (at low frequency) at -180°. As the distribution frequency increases, the impedance phase angle rotates in the clockwise direction with the real part of the dynamic impedance becoming positive at frequencies above 0.6 cps (Hz). The system showed no tendency to be unstable during the data run even at frequencies below 0.6 cps (Hz). Again the boiler-feed-system impedance provided sufficient stabilization.

SUMMARY OF RESULTS

Experimental frequency-response techniques were used to measure the inlet dynamic impedance of a forced-flow single-tube boiler. The results of these measurements may be summarized as follows:

1. For all conditions investigated, the boiler dynamic impedance was found to have a negative real part over some frequency range.

2. A negative real part of the boiler dynamic impedance was found to exist even though the slope of the curve for steady-state pressure drop against flow was positive.

3. When the slope of the curve for steady-state pressure drop against flow for the boiler was negative, the real part of the dynamic impedance was negative at low frequencies (in agreement with the steady-state curve) but became positive at higher frequencies (e.g., above 0.6 cps (Hz)).

4. Over the range of conditions investigated, boiler-inlet impedance was found to be a function of exit vapor quality. At low frequencies, the magnitude of the impedance was larger at the higher qualities. At high frequencies, the magnitudes were approximately the same over the quality range encountered.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 7, 1967,
120-27-04-27-22.

APPENDIX - SYMBOLS

f frequency, cps (Hz)

L_{sc} subcooled length, in. (cm)

ΔP_B steady-state boiler pressure drop, psi (N/m^2)

P_I Freon mean pressure at boiler inlet, psia (N/m^2)

P_I' Freon perturbation pressure at boiler inlet, psi (N/m^2)

P_O Freon mean pressure at boiler exit, psi (N/m^2)

t_{FI} Freon temperature at boiler inlet, ^oF (^oK)

t_{FO} Freon temperature at boiler exit, ^oF (^oK)

w_F Freon mean flow rate, lb/hr (kg/sec)

w_F' Freon perturbation flow rate, lb/hr (kg/sec)

w_W water flow rate, lb/hr (kg/sec)

$\varphi_{P_I'}$ phase angle of Freon perturbation pressure at boiler inlet relative to command oscillator, deg

$\varphi_{w_F'}$ phase angle of Freon perturbation flow rate relative to command oscillator, deg

REFERENCES

1. Gouse, S. William, Jr.: An Index to the Two-Phase Gas-Liquid Flow Literature. Part 1. Rep. No. DSR-8734-1 (DDC No. AD-411512), May 1963; Part 2. Rep. No. DSR-8734-4 (DDC No. AD-607180), Massachusetts Inst. Tech., Sept. 1964.

2. Balzhizer, R. E.; Clark, J. A.; Colver, C. P.; Hucke, E. E.; and Merte, H., Jr.: Literature Survey on Liquid Metal Boiling. Rep. No. 04526-2-F (AFASD-TR-61-594), Michigan University, Dec. 1961.

3. Regetz, John D., Jr.: An Experimental Determination of the Dynamic Response of a Long Hydraulic Line. NASA TN D-576, 1960.

4. Kinsler, Lawrence E.; and Frey, Austin, R.: Fundamentals of Acoustics. John Wiley & Sons, Inc., 1950.

5. Grace, Thomas M.; and Krejsa, Eugene A.: Analytical and Experimental Study of Boiler Instabilities Due to Feed-System - Subcooled Region Coupling. NASA TN D-3961, 1967.

TABLE I. - MEAN OPERATING CONDITIONS

(a) Freon

Run	Flow rate, w_F		Absolute inlet pressure, P_I		Absolute exit pressure, P_O		Temperature in, t_{FI}		Temperature out, t_{FO}		Freon exit quality.	Subcooled length, L_{sc}	
	lb/hr	kg/sec	lb/in.^{2}	N/m^2	lb/in.^{2}	N/m^2	^oF	^oK	^oF	^oK	x, percent	in.	cm
1	604	0.076	26.6	183×10^3	16.5	114×10^3	74	297	129	327	12	32.0	81.3
2	656	.083	26.4	182	16.2	112×10^3	78	299	131	328	13	32.0	81.3
3	445	.056	25.5	176	14.3	987×10^2	71	295	125	325	29	22.0	55.9
4	286	.036	23.5	162	14.3	987×10^2	67	293	120	322	50	8.0	20.3
5	175	.022	19.1	132	14.4	993×10^2	68	293	117	321	63	4.0	10.2
6	643	.081	30.1	208	17.2	119×10^3	76	298	135	330	23	27.0	68.6
7	453	.057	28.1	194	15.4	106×10^3	74	297	128	327	37	16.0	40.6
8	287	.036	21.8	150	14.8	102×10^3	69	294	119	322	45	5.4	13.7
9	175	.022	17.7	122	14.3	987×10^2	69	294	118	321	47	2.0	5.1
10	453	.057	25.7	177	15.7	108×10^3	73	296	126	326	31	9.0	22.9
11	597	.075	32.4	223	18.0	124×10^3	76	298	139	333	31	20.0	50.8

(b) Water

Run	Flow rate, w_W		Temperature at station -																	
			1		2		3		4		5		6		7		8		9	
	lb/hr	kg/sec	^oF	^oK	^oF	^oK	^oF	^oK	^oF	^oK	^oF	^oK	^oF	^oK	^oF	^oK	^oF	^oK	^oF	^oK
1	690	0.0876	208	371	206	370	204	369	203	368	201	367	198	366	197	365	194	363	192	362
2	698	.088	211	373	209	372	207	371	205	369	203	368	200	367	199	366	196	364	193	363
3	699	.088	209	372	205	369	204	369	202	368	200	367	197	365	196	364	193	363	191	362
4	685	.086	211	373	210	372	208	371	206	370	203	368	200	367	199	366	196	364	193	363
5	675	.085	210	372	209	372	209	372	209	372	208	371	207	371	206	370	201	367	197	365
6	673	.085	231	384	228	382	225	381	223	379	220	378	216	376	215	375	211	373	207	371
7	724	.091	231	384	230	383	229	383	227	382	224	380	219	377	217	376	213	374	210	372
8	699	.088	230	383	230	383	230	383	229	383	228	382	227	382	226	381	219	377	214	374
9	699	.088	231	384	231	384	231	384	231	384	230	383	230	383	230	383	227	382	221	378
10	699	.088	249	394	249	394	248	393	248	393	247	392	244	391	239	388	234	386	229	383
11	680	.085	250	394	248	393	246	392	243	391	240	389	234	386	231	384	227	382	223	379

TABLE II. - BOILER PERTURBATION DATA

(a) Run 1; Freon flow rate, 604 pounds per hour (0.076 kg/sec); boiler exit quality, 12 percent; inlet water temperature, 208° F (371° K)

Frequency, f, cps (Hz)	Freon flow at boiler inlet			Pressure at boiler inlet			Boiler-inlet impedance		
	Amplitude,[a] $\lvert w'_F \rvert$		Phase relative to oscillator, $\varphi_{w'_F}$, deg	Amplitude,[a] $\lvert P'_I \rvert$		Phase relative to oscillator, $\varphi_{P'_I}$, deg	Amplitude, $\lvert P'_I/w'_F \rvert$		Phase, $\varphi_{P'_I} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	$(N/m^2)/(kg/sec)$	
0.04	59	0.0074	-20	0.05	345	-15	0.8×10^{-3}	4.38×10^{4}	5
.04	59	.0074	-16	.03	207	-245	.5	2.74	-229
.055	57	.0072	-17	.01	69	-266	.2	1.09	-249
.06	55	.0069	-20	.03	207	-25	.5	2.74	-5
.07	57	.0072	-20	.01	69	-81	.2	1.09	-61
.085	59	.0074	-20	.03	207	-103	.5	2.74	-83
.085	55	.0069	-22	.04	276	-95	.7	3.84	-73
.10	56	.0070	-22	.04	276	-112	.7	3.84	-90
.12	55	.0069	-22	.04	276	-153	.7	3.84	-131
.15	56	.0070	-23	.06	414	-192	1.1	6.04	-169
.20	55	.0069	-24	.06	414	-215	1.1	6.04	-191
.30	53	.0067	-28	.06	414	-242	1.1	6.04	-214
.40	52	.0065	-32	.08	552	-242	1.5	8.23	-210
.50	48	.0060	-34	.11	759	-281	2.3	12.6	-247
.60	44	.0055	-36	.12	828	-294	2.7	14.8	-258
.70	44	.0055	-36	.13	897	-308	3.0	16.4	-272
.85	41	.0052	-37	.13	897	-330	3.2	17.5	-293
1.0	40	.0050	-38	.14	966	-341	3.5	19.2	-303
1.2	39	.0049	-38	.12	828	-353	3.1	17.0	-315
1.5	39	.0049	-36	.10	690	-352	2.6	14.2	-316
1.7	39	.0049	-38	.08	552	-353	2.0	11.0	-315
2.0	40	.0050	-40	.09	621	-345	2.2	12.1	-305
2.2	40	.0050	-38	.11	759	-334	2.8	15.3	-296
2.5	40	.0050	-40	.14	966	-340	3.5	19.2	-300
3.0	43	.0054	-44	.15	1036	-352	3.5	19.2	-308
3.5	44	.0055	-50	.15	1036	-355	3.4	18.6	-305
4.0	45	.0057	-62	.17	1172	-364	3.8	20.8	-302

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(b) Run 2; Freon flow rate, 656 pounds per hour (0.083 kg/sec); boiler exit quality, 13 percent; inlet water temperature, 211° F (373° K)

Frequency, f, cps (Hz)	Freon flow at boiler inlet			Pressure at boiler inlet			Boiler-inlet impedance		
	Amplitude,[a] $\lvert w'_F \rvert$		Phase relative to oscillator, $\varphi_{w'_F}$, deg	Amplitude,[a] $\lvert P'_I \rvert$		Phase relative to oscillator, $\varphi_{P'_I}$, deg	Amplitude, $\lvert P'_I/w'_F \rvert$		Phase, $\varphi_{P'_I} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	(N/m^2)/(kg/sec)	
0.04	79	0.0099	-16	0.19	1310	-214	2.6×10^{-3}	14.3 ×10^4	-192
.055	73	.0092	-18	.14	955	-227	1.9	10.4	-209
.07	79	.0099	-17	.13	896	-217	1.6	8.77	-200
.10	75	.0094	-19	.15	1050	-202	2.0	11.0	-181
.15	75	.0094	-20	.19	1310	-222	2.5	13.7	-202
.20	60	.0075	-22	.19	1310	-240	3.2	17.5	-218
.20	72	.0091	-22	.19	1310	-240	2.6	14.3	-218
.25	72	.0091	-23	.18	1240	-252	2.5	13.7	-229
.30	72	.0091	-24	.19	1310	-259	2.6	14.3	-234
.35	71	.0089	-26	.20	1380	-270	2.8	15.4	-244
.40	57	.0072	-28	.21	1450	-275	3.7	20.3	-247
.55	65	.0082	-31	.23	1590	-298	3.5	19.2	-267
.70	64	.0080	-32	.25	1720	-315	3.9	21.4	-283
.85	59	.0074	-32	.23	1590	-330	3.9	21.4	-298
1.0	59	.0074	-33	.22	1520	-342	3.7	20.3	-309
1.2	57	.0072	-33	.18	1240	-350	3.2	17.5	-317
1.35	55	.0069	-36	.14	955	-353	2.5	13.7	-317
1.5	57	.0072	-34	.13	896	-342	2.3	12.6	-308
1.55	55	.0069	-37	.12	838	-342	2.2	12.1	-305
1.65	55	.0069	-36	.12	838	-333	2.2	12.1	-297
1.8	57	.0072	-36	.16	1104	-322	2.8	15.4	-296
2.0	56	.0070	-39	.19	1310	-322	3.4	18.6	-283
2.5	56	.0070	-40	.26	1790	-332	4.6	25.2	-292
3.0	56	.0070	-45	.27	1860	-345	4.8	26.3	-300
3.5	55	.0069	-47	.27	1860	-344	4.9	26.9	-297
4.0	57	.0072	-53	.28	1930	-346	4.9	26.9	-293

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(c) Run 3; Freon flow rate, 445 pounds per hour (0.056 kg/sec); boiler exit quality, 29 percent; inlet water temperature, 209° F (372° K)

Frequency, f, cps (Hz)	Freon flow at boiler inlet			Pressure at boiler inlet			Boiler-inlet impedance		
	Amplitude,[a] $\lvert w'_F \rvert$		Phase relative to oscillator, $\varphi_{w'_F}$, deg	Amplitude,[a] $\lvert P'_I \rvert$		Phase relative to oscillator, $\varphi_{P'_I}$, deg	Amplitude, $\lvert P'_I/w'_F \rvert$		Phase $\varphi_{P'_I} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	$(N/m^2)/(kg/sec)$	
0.05	43	0.0054	-13	0.27	1860	-30	6.3×10^{-3}	34.5×10^{4}	-17
.07	43	.0054	-12	.28	1930	-43	6.5	35.6	-31
.10	43	.0054	-13	.26	1790	-63	6.0	32.8	-50
.15	43	.0054	-14	.23	1590	-85	5.4	29.6	-71
.20	47	.0059	-17	.22	1520	-110	4.7	25.8	-93
.30	45	.0057	-20	.18	1240	-151	4.0	21.9	-131
.40	45	.0057	-25	.15	1030	-194	3.3	18.1	-169
.50	45	.0057	-31	.15	1030	-235	3.3	18.1	-204
.60	41	.0052	-33	.14	966	-262	3.4	18.6	-229
.70	41	.0052	-37	.14	966	-287	3.4	18.6	-250
.85	37	.0047	-36	.13	898	-310	3.5	19.2	-274
1.0	37	.0047	-38	.13	898	-339	3.5	19.2	-301
1.2	35	.0044	-37	.10	690	-359	2.9	15.9	-322
1.3	33	.0042	-37	.08	552	-361	2.4	13.2	-324
1.4	35	.0044	-35	.07	483	-362	2.0	10.96	-327
1.5	37	.0047	-37	.06	424	-371	1.6	8.78	-334
1.6	33	.0042	-37	.05	345	-358	1.5	8.22	-321
1.8	35	.0044	-37	.04	276	-332	1.1	6.03	-295
1.9	35	.0044	-39	.05	345	-323	1.4	7.68	-284
2.0	37	.0047	-42	.07	483	-327	1.9	10.42	-285
2.1	34	.0043	-41	.08	552	-320	2.3	12.6	-279
2.2	35	.0044	-42	.10	690	-324	2.9	15.9	-282
2.5	36	.0045	-46	.11	759	-344	3.1	17.0	-298
2.7	34	.0043	-46	.11	759	-344	3.2	17.5	-298
3.0	37	.0047	-51	.10	690	-347	2.7	14.8	-296
3.0	35	.0044	-48	.10	690	-344	2.9	15.9	-296
3.2	35	.0044	-53	.11	759	-340	3.1	17.0	-287
3.5	37	.0047	-57	.13	898	-349	3.5	19.2	-292
3.75	35	.0044	-60	.15	1030	-363	4.3	23.6	-303
4.0	37	.0047	-63	.11	759	-378	3.0	16.5	-315
4.0	36	.0045	-61	.12	828	-375	3.3	18.1	-314

[a] Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(d) Run 4; Freon flow rate, 286 pounds per hour (0.036 kg/sec); boiler exit quality, 50 percent; inlet water temperature, 211° F (373° K)

Frequency, f, cps (Hz)	Freon flow at boiler inlet			Pressure at boiler inlet			Boiler-inlet impedance		
	Amplitude,[a] $\lvert w'_F \rvert$		Phase relative to oscillator, $\varphi_{w'_F}$, deg	Amplitude,[a] $\lvert P'_I \rvert$		Phase relative to oscillator, $\varphi_{P'_I}$, deg	Amplitude, $\lvert P'_I/w'_F \rvert$		Phase, $\varphi_{P'_I} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	(N/m^2)/(kg/sec)	
0.04	21	0.0026	-12	0.56	3860	-32	26.2×10^{-3}	144×10^4	-20
.07	24	.0030	-12	.52	3580	-47	21.8	118	-35
.10	25	.0031	-7	.58	4000	-52	22.0	121	-45
.20	31	.0039	-1	.63	4340	-90	20.4	112	-89
.40	45	.0057	-22	.58	4000	-179	12.8	700×10^3	-157
.70	36	.0045	-47	.30	2070	-264	8.2	450	-217
1.0	27	.0034	-55	.21	1390	-306	7.8	428	-251
1.5	23	.0029	-51	.14	966	-357	6.3	346	-306
1.8	23	.0029	-51	.10	690	-377	4.2	230	-326
2.0	23	.0029	-53	.09	621	-375	4.1	225	-322
2.1	23	.0029	-55	.07	483	-364	3.1	170	-309
2.2	23	.0029	-56	.10	690	-359	4.2	230	-303
2.4	21	.0026	-58	.12	828	-374	5.6	307	-316
2.5	23	.0029	-58	.12	828	-383	5.5	302	-325
2.7	23	.0029	-57	.13	898	-410	5.6	307	-353
2.8	21	.0026	-57	.15	1030	-424	6.9	378	-367
3.0	24	.0030	-57	.13	898	-453	5.5	302	-396
3.1	24	.0030	-58	.12	828	-480	5.0	274	-422
3.3	25	.0031	-63	.08	552	-540	3.0	165	-477
3.5	27	.0034	-71	.07	483	-602	2.7	148	-531
4.0	27	.0034	-78	.08	552	-687	3.1	170	-609

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(e) Run 5; Freon flow rate, 175 pounds per hour (0.022 kg/sec); boiler exit quality, 63 percent; inlet water temperature, 210° F (372° K)

Frequency, f, cps (Hz)	Freon flow at boiler inlet			Pressure at boiler inlet			Boiler-inlet impedance		
	Amplitude,[a] $\lvert w'_F \rvert$		Phase relative to oscillator, $\varphi_{w'_F}$, deg	Amplitude,[a] $\lvert P'_I \rvert$		Phase relative to oscillator, $\varphi_{P'_I}$, deg	Amplitude, $\lvert P'_I/w'_F \rvert$		Phase, $\varphi_{P'_I} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	$(N/m^2)/(kg/sec)$	
0.05	8	0.0010	-3	0.31	2140	-32	38.8×10^{-3}	213×10^4	-29
.07	8	.0010	-6	.30	2070	-35	37.6	206	-29
.09	8	.0010	-2	.31	2140	-37	38.8	213	-35
.10	9	.0011	5	.34	2340	-34	37.8	207	-39
.15	11	.0014	8	.32	2210	-42	29.1	160	-50
.20	11	.0014	3	.32	2210	-49	29.1	160	-52
.30	13	.0016	8	.28	1930	-72	21.6	118	-80
.40	15	.0019	11	.34	2340	-85	22.7	124	-96
.50	17	.0021	4	.32	2210	-105	18.8	103	-109
.60	23	.0029	-8	.37	2550	-130	16.1	882×10^3	-122
.70	28	.0035	-21	.40	2760	-161	14.3	785	-140
.80	27	.0034	-40	.36	2480	-190	13.3	729	-150
.90	27	.0034	-55	.31	2140	-217	11.5	631	-162
1.0	29	.0036	-60	.34	2340	-233	11.7	642	-173
1.5	13	.0016	-79	.12	827	-312	9.2	505	-233
2.0	13	.0016	-101	.09	621	-368	6.9	378	-267
2.5	11	.0014	-81	.06	414	-390	5.6	307	-309
3.0	11	.0014	-110	.05	345	-452	4.5	247	-342
3.3	11	.0014	-87	.03	207	-503	2.7	148	-416
3.5	12	.0015	-92	.03	207	-540	2.5	137	-448
3.7	12	.0015	-103	.05	345	-610	4.2	230	-507
3.8	11	.0014	-103	.05	345	-630	4.5	247	-527
3.9	12	.0015	-110	.07	483	-645	5.8	318	-535
4.0	32	.0040	-142	.08	552	-687	2.5	137	-545
4.2	11	.0014	-121	.08	552	-697	7.3	400	-576

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(f) Run 6; Freon flow rate, 643 pounds per hour (0.081 kg/sec); boiler exit quality, 23 percent; inlet water temperature, 231° F (384° K)

Frequency, f, cps (Hz)	Freon flow at boiler inlet			Pressure at boiler inlet			Boiler-inlet impedance		
	Amplitude,[a] $\lvert w'_F \rvert$		Phase relative to oscillator, $\varphi_{w'_F}$, deg	Amplitude,[a] $\lvert P'_I \rvert$		Phase relative to oscillator, $\varphi_{P'_I}$, deg	Amplitude, $\lvert P'_I/w'_F \rvert$		Phase, $\varphi_{P'_I} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	$(N/m^2)/(kg/sec)$	
0.04	52	0.0065	-20	0.25	1720	-32	4.8×10^{-3}	26.3×10^{4}	-12
.06	56	.0070	-18	.29	2000	-40	5.2	28.5	-22
.08	56	.0070	-20	.31	2140	-50	5.5	30.2	-30
.10	59	.0074	-16	.29	2000	-64	4.9	26.8	-48
.12	57	.0072	-21	.25	1720	-73	4.4	24.1	-52
.15	60	.0075	-17	.22	1520	-87	3.7	20.3	-60
.20	59	.0074	-21	.22	1520	-105	3.7	20.3	-84
.30	59	.0074	-25	.19	1310	-147	3.2	17.5	-122
.40	55	.0069	-30	.17	1170	-193	3.1	17.0	-163
.50	53	.0067	-33	.17	1170	-228	3.2	17.5	-195
.60	51	.0064	-33	.17	1170	-257	3.3	18.1	-224
.70	48	.0060	-32	.15	1035	-270	3.1	17.0	-238
.80	47	.0059	-33	.16	1100	-288	3.4	18.6	-255
1.0	45	.0056	-36	.16	1100	-326	3.6	19.7	-290
1.2	44	.0055	-33	.12	827	-334	2.7	14.8	-301
1.4	43	.0054	-33	.09	621	-339	2.1	11.5	-306
1.5	45	.0056	-35	.08	552	-330	1.8	98.7×10^{3}	-295
1.6	44	.0055	-35	.07	483	-324	1.6	87.8	-289
1.7	44	.0055	-36	.08	552	-317	1.8	98.7	-281
2.0	44	.0055	-38	.12	827	-308	2.7	14.8×10^{4}	-270
2.2	45	.0056	-39	.16	1100	-309	3.6	19.7	-270
2.5	47	.0059	-42	.20	1380	-317	4.3	23.0	-275
2.8	45	.0056	-43	.22	1520	-327	4.9	26.8	-284
3.0	47	.0059	-45	.24	1660	-337	5.1	28.0	-292
3.0	47	.0059	-46	.23	1590	-334	4.9	26.8	-288
3.4	48	.0060	-50	.23	1590	-344	4.8	26.3	-294
3.5	48	.0060	-51	.23	1590	-342	4.8	26.3	-291
4.0	48	.0060	-54	.25	1720	-362	5.2	28.5	-308
4.0	48	.0060	-55	.24	1660	-361	5.0	27.4	-306
4.5	47	.0059	-58	.18	1240	-370	3.8	20.8	-312
5.0	48	.0060	-64	.16	1100	-342	3.3	18.1	-278

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(g) Run 7; Freon flow rate, 453 pounds per hour (0.057 kg/sec); boiler exit quality, 37 percent; inlet water temperature, 231° F (384° K)

Frequency, f, cps (Hz)	Freon flow at boiler inlet			Pressure at boiler inlet			Boiler-inlet impedance		
	Amplitude,[a] $\lvert w'_F \rvert$		Phase relative to oscillator, $\varphi_{w'_F}$, deg	Amplitude,[a] $\lvert P'_I \rvert$		Phase relative to oscillator, $\varphi_{P'_I}$, deg	Amplitude, $\lvert P'_I/w'_F \rvert$		Phase $\varphi_{P'_I} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	(N/m^2)/(kg/sec)	
0.04	31	0.0039	-12	0.66	4550	-35	21.3×10^{-3}	116.8×10^4	-23
.06	32	.0040	-15	.68	4690	-44	21.2	116.5	-29
.10	33	.0041	-13	.73	5030	-55	22.1	121.0	-42
.15	35	.0044	-12	.66	4550	-75	18.9	103.5	-63
.20	36	.0045	-11	.65	4480	-87	18.1	99.0	-76
.30	43	.0054	-16	.61	4200	-122	14.2	77.7	-106
.40	44	.0055	-25	.50	3440	-155	11.4	62.3	-130
.60	40	.0050	-40	.34	2340	-217	8.5	46.6	-177
.80	35	.0044	-45	.24	1650	-258	6.8	37.6	-213
1.0	35	.0044	-50	.23	1580	-270	6.6	36.0	-220
1.2	29	.0036	-48	.19	1310	-295	6.6	36.0	-247
1.35	29	.0036	-51	.18	1240	-309	6.2	34.0	-258
1.5	27	.0034	-48	.17	1170	-320	6.3	34.6	-272
1.65	28	.0035	-50	.16	1100	-335	5.7	31.4	-285
1.8	27	.0034	-46	.15	1030	-342	5.6	30.5	-296
2.0	28	.0035	-52	.15	1030	-366	5.4	29.4	-314
2.2	27	.0034	-48	.13	895	-372	4.8	26.4	-324
2.25	27	.0034	-51	.12	825	-370	4.5	24.4	-319
2.40	28	.0035	-50	.11	760	-375	3.9	21.5	-325
2.70	28	.0035	-51	.10	690	-390	3.6	19.6	-339
2.8	29	.0036	-51	.10	690	-386	3.5	18.9	-335
3.0	29	.0036	-54	.11	760	-395	3.8	20.8	-341
3.2	29	.0036	-54	.09	620	-426	3.1	17.0	-372
3.5	32	.0040	-54	.09	620	-462	2.8	15.4	-408

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(h) Run 8; Freon flow rate, 287 pounds per hour (0.036 kg/sec); boiler exit quality, 45 percent; inlet water temperature, 230° F (383° K)

Frequency, f, cps (Hz)	Freon flow at boiler inlet			Pressure at boiler inlet			Boiler-inlet impedance		
	Amplitude,[a] $\lvert w'_F \rvert$		Phase relative to oscillator, $\varphi_{w'_F}$, deg	Amplitude,[a] $\lvert P'_I \rvert$		Phase relative to oscillator, $\varphi_{P'_I}$, deg	Amplitude, $\lvert P'_I/w'_F \rvert$		Phase, $\varphi_{P'_I} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	(N/m^2)/(kg/sec)	
0.04	16	0.0020	-12	0.45	3100	-29	28.2×10^{-3}	154.1×10^4	-17
.06	17	.0021	-14	.45	3100	-35	26.5	145.0	-21
.08	19	.0024	-7	.48	3300	-28	25.2	138.2	-21
.10	21	.0026	-8	.49	3370	-35	23.3	128.0	-27
.15	23	.0029	-4	.45	3100	-45	19.6	107.0	-41
.20	23	.0029	-2	.47	3240	-55	20.4	112.0	-53
.30	23	.0029	-8	.40	2760	-80	17.4	95.4	-72
.40	28	.0035	-4	.44	3030	-92	15.7	86.3	-88
.60	31	.0039	-21	.37	2550	-141	11.9	65.4	-120
.80	29	.0036	-34	.30	2070	-180	10.3	57.7	-146
1.0	28	.0035	-46	.22	1510	-220	7.9	43.0	-174
1.2	25	.0031	-51	.19	1310	-240	7.6	41.6	-189
1.5	25	.0031	-50	.16	1100	-272	6.4	35.1	-222
2.0	23	.0029	-54	.14	963	-310	6.1	33.4	-256
2.5	18	.0023	-64	.10	690	-348	5.6	30.5	-284
3.0	17	.0021	-67	.09	610	-383	5.3	29.0	-316
3.5	19	.0024	-69	.08	550	-424	4.2	23.1	-355
4.0	20	.0025	-75	.07	482	-477	3.5	19.2	-402
4.5	23	.0029	-86	.06	413	-590	2.6	14.3	-504

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(i) Run 9; Freon flow rate, 175 pounds per hour (0.022 kg/sec); boiler exit quality, 47 percent; inlet water temperature, 231° F (384° K)

Frequency, f, cps (Hz)	Freon flow at boiler inlet			Pressure at boiler inlet			Boiler-inlet impedance		
	Amplitude,[a] $\lvert w'_F \rvert$		Phase relative to oscillator, $\varphi_{w'_F}$, deg	Amplitude,[a] $\lvert P'_I \rvert$		Phase relative to oscillator, $\varphi_{P'_I}$, deg	Amplitude, $\lvert P'_I/w'_F \rvert$		Phase, $\varphi_{P'_I} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	(N/m^2)/(kg/sec)	
0.04	9.4	0.0012	-7	0.19	1310	-13	20.2×10^{-3}	111.0×10^4	-6
.06	9.4	.0012	-15	.19	1310	-30	20.2	111.0	-15
.08	11.0	.0014	-12	.19	1310	-16	17.3	94.6	-4
.10	11.0	.0014	-13	.19	1310	-35	17.3	94.6	-23
.15	9.4	.0012	-11	.19	1310	-41	20.2	111.0	-30
.20	11.0	.0014	-15	.18	1240	-40	16.4	89.7	-25
.30	12.0	.0015	-11	.18	1240	-45	15.0	82.3	-34
.40	12.0	.0015	-10	.18	1240	-57	15.0	82.3	-47
.60	11.0	.0014	-20	.15	1030	-80	13.6	74.8	-60
.80	13.0	.0016	-15	.20	1380	-90	11.5	63.3	-75
1.0	13.0	.0016	-23	.19	1310	-111	14.6	80.1	-88
1.5	19.0	.0024	-46	.25	1720	-167	13.2	72.1	-121
2.0	17.0	.0021	-73	.19	1310	-230	11.2	61.3	-157
2.5	16.0	.0020	-99	.14	965	-294	8.7	47.9	-195
3.0	12.0	.0015	-99	.11	758	-296	9.2	50.3	-197
3.5	12.0	.0015	-121	.12	826	-336	10.0	54.8	-215
4.0	9.4	.0012	-117	.11	758	-342	11.7	64.1	-225

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(j) Run 10; Freon flow rate, 453 pounds per hour (0.057 kg/sec); boiler exit quality, 31 percent; inlet water temperature, 249° F (394° K)

Frequency, f, cps (Hz)	Freon flow at boiler inlet: Amplitude,[a] $\lvert w'_F \rvert$, lb/hr	Freon flow at boiler inlet: Amplitude,[a] $\lvert w'_F \rvert$, kg/sec	Freon flow at boiler inlet: Phase relative to oscillator, $\varphi_{w'_F}$, deg	Pressure at boiler inlet: Amplitude,[a] $\lvert P'_I \rvert$, psi	Pressure at boiler inlet: Amplitude,[a] $\lvert P'_I \rvert$, N/m^2	Pressure at boiler inlet: Phase relative to oscillator, $\varphi_{P'_I}$, deg	Boiler-inlet impedance: Amplitude, $\lvert P'_I/w'_F \rvert$, psi/(lb/hr)	Boiler-inlet impedance: Amplitude, $\lvert P'_I/w'_F \rvert$, $(N/m^2)/(kg/sec)$	Boiler-inlet impedance: Phase $\varphi_{P'_I} - \varphi_{w'_F}$, deg
0.04	37	0.0047	-11	1.05	7240	-30	28.4×10^{-3}	155.5×10^{4}	-19
.06	39	.0049	-12	1.10	7580	-32	28.2	155.4	-20
.08	40	.0050	-10	.95	6550	-39	23.8	130.2	-29
.10	40	.0050	-10	.90	6200	-48	22.5	123.3	-38
.15	43	.0054	-7	.90	6200	-60	20.9	114.8	-53
.20	44	.0055	-9	.81	5580	-69	18.4	101.0	-60
.30	48	.0060	-12	.71	4900	-92	14.8	81.0	-80
.40	51	.0064	-15	.67	4610	-116	13.1	72.0	-101
.60	51	.0064	-24	.57	3930	-159	11.2	61.3	-135
.80	48	.0060	-30	.43	2960	-192	8.9	49.0	-162
1.0	47	.0059	-26	.40	2760	-216	8.5	46.6	-190
1.2	43	.0054	-38	.31	2140	-237	7.2	39.5	-199
1.5	41	.0052	-40	.26	1790	-262	6.3	34.8	-222
1.8	39	.0049	-43	.23	1580	-287	5.9	32.3	-244
2.0	39	.0049	-44	.24	1650	-296	6.2	33.7	-252
2.5	37	.0047	-47	.21	1450	-323	5.7	31.1	-276
3.0	39	.0049	-51	.18	1240	-343	4.6	25.3	-292
3.2	39	.0049	-53	.17	1170	-353	4.4	23.9	-300
3.5	39	.0049	-55	.13	895	-355	3.3	18.3	-300
3.8	39	.0049	-58	.11	758	-359	2.8	15.5	-301
4.0	40	.0050	-61	.11	758	-360	2.7	15.1	-299
4.2	41	.0052	-64	.08	551	-342	2.0	10.8	-288
4.3	40	.0050	-66	.10	690	-331	2.5	13.7	-265
4.5	41	.0052	-69	.16	1100	-325	3.9	21.4	-256
5.0	39	.0049	-78	.33	2270	-353	8.5	46.4	-275

[a]Zero to peak.

TABLE II. - Concluded. BOILER PERTURBATION DATA

(k) Run 11; Freon flow rate, 597 pounds per hour (0.075 kg/sec); boiler exit quality, 31 percent; inlet water temperature, 250° F (394° K)

Frequency, f, cps (Hz)	Freon flow at boiler inlet			Pressure at boiler inlet			Boiler-inlet impedance		
	Amplitude,[a] $\lvert w'_F \rvert$		Phase relative to oscillator, $\varphi_{w'_F}$, deg	Amplitude,[a] $\lvert P'_I \rvert$		Phase relative to oscillator, $\varphi_{P'_I}$, deg	Amplitude, $\lvert P'_I/w'_F \rvert$		Phase, $\varphi_{P'_I} - \varphi_{w'_F}$, deg
	lb/hr	kg/sec		psi	N/m^2		psi/(lb/hr)	$(N/m^2)/(kg/sec)$	
0.04	51	0.0064	-6	1.71	11 800	-28	33.5×10^{-3}	183.5×10^{4}	-22
.06	51	.0064	-2	1.66	11 450	-32	32.6	178.8	-30
.08	51	.0064	-6	1.57	10 800	-43	30.8	168.6	-37
.10	52	.0065	-6	1.52	10 500	-50	29.3	160.5	-44
.15	56	.0071	-5	1.38	9 500	-67	24.6	134.8	-62
.20	60	.0075	-7	1.24	8 550	-80	20.7	113.5	-73
.30	65	.0082	-13	1.09	7 500	-115	16.8	92.0	-102
.40	65	.0082	-20	.85	5 850	-146	13.1	71.7	-126
.60	60	.0075	-29	.50	3 440	-199	8.3	45.5	-170
.80	55	.0069	-32	.33	2 280	-239	6.0	32.9	-207
1.0	52	.0065	-36	.27	1 860	-268	5.2	28.5	-232
1.2	48	.0060	-35	.25	1 730	-297	5.2	28.5	-262
1.5	47	.0059	-35	.20	1 380	-331	4.3	23.6	-296
1.7	47	.0059	-34	.17	1 170	-343	3.8	20.8	-309
1.85	47	.0059	-37	.14	965	-349	3.0	16.5	-312
2.0	48	.0060	-37	.11	760	-352	2.3	12.6	-315
2.2	47	.0059	-37	.10	690	-346	2.1	11.5	-309
2.4	48	.0060	-38	.08	551	-342	1.7	9.3	-304
2.5	49	.0062	-38	.08	551	-332	1.6	8.8	-294
2.7	49	.0062	-40	.11	760	-313	2.2	12.1	-273
3.0	49	.0062	-43	.14	965	-315	2.9	15.9	-272
3.5	51	.0064	-49	.20	1 380	-324	3.9	21.4	-275
4.0	52	.0065	-54	.26	1 790	-327	5.0	27.4	-273

[a]Zero to peak.

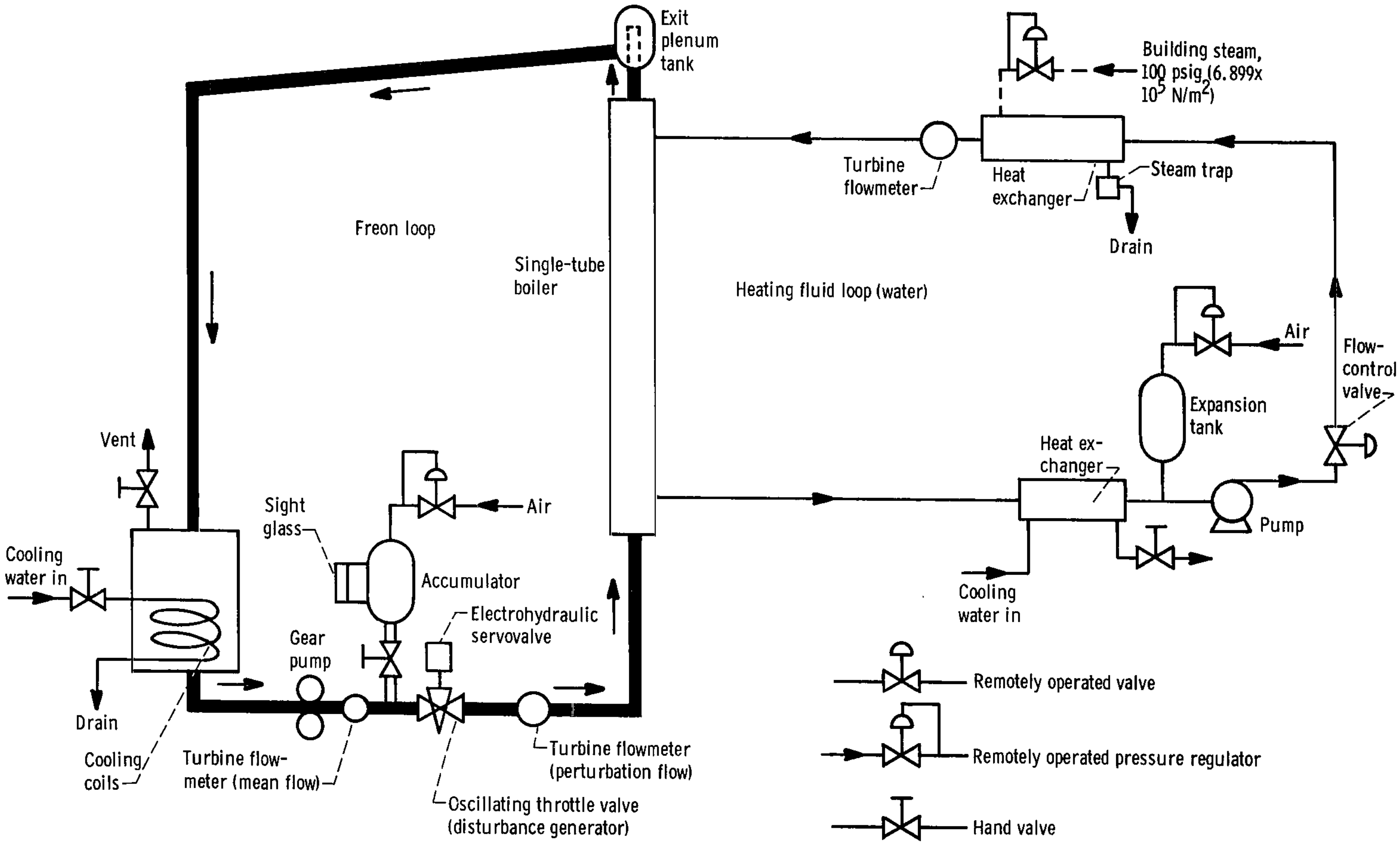
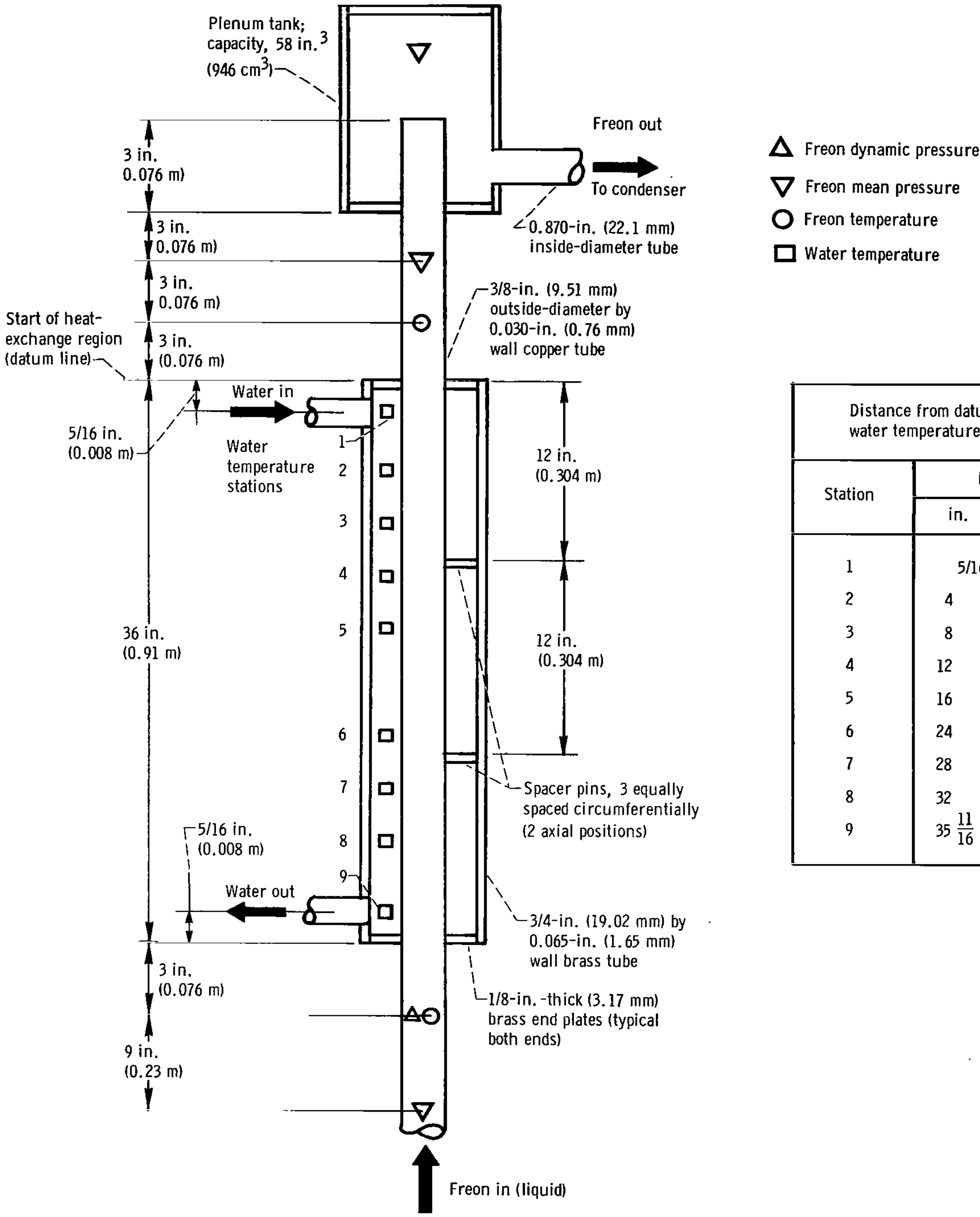


Figure 1. - Boiling dynamics facility.



Distance from datum line to water temperature stations		
Station	Distance	
	in.	m
1	5/16	0.008
2	4	.101
3	8	.203
4	12	.304
5	16	.406
6	24	.609
7	28	.710
8	32	.812
9	$35\frac{11}{16}$	.905

Figure 2. - Schematic drawing of single-tube-boiler test section.

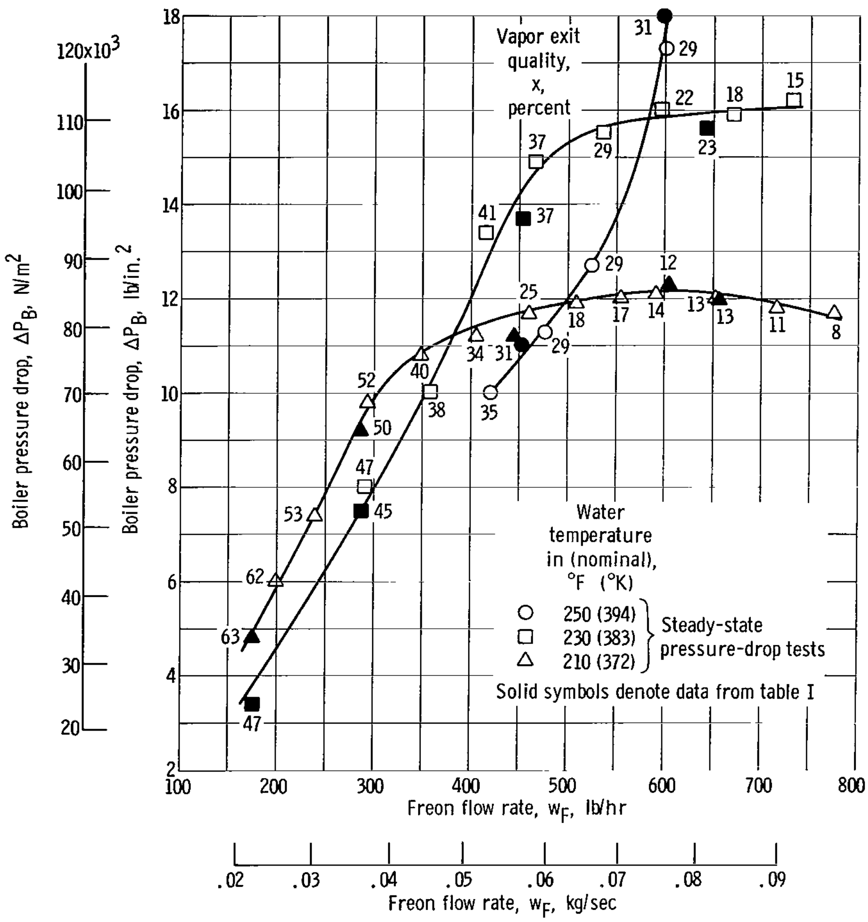
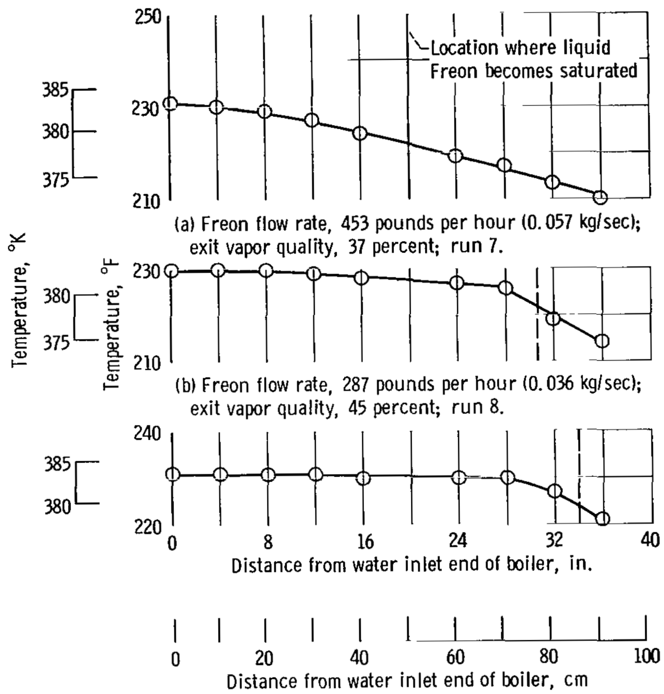


Figure 3. - Steady-state boiler pressure drop as function of flow rate for different values of water inlet temperature and Freon exit quality.

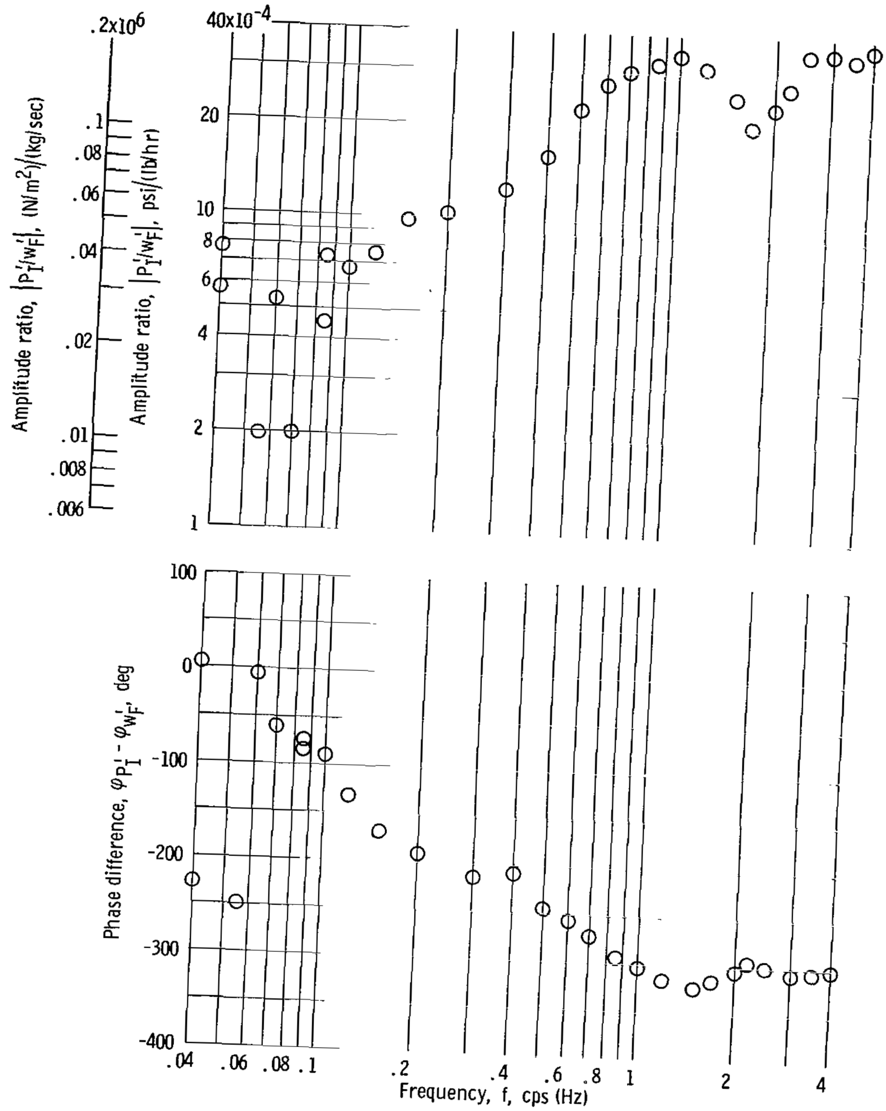


(a) Freon flow rate, 453 pounds per hour (0.057 kg/sec); exit vapor quality, 37 percent; run 7.

(b) Freon flow rate, 287 pounds per hour (0.036 kg/sec); exit vapor quality, 45 percent; run 8.

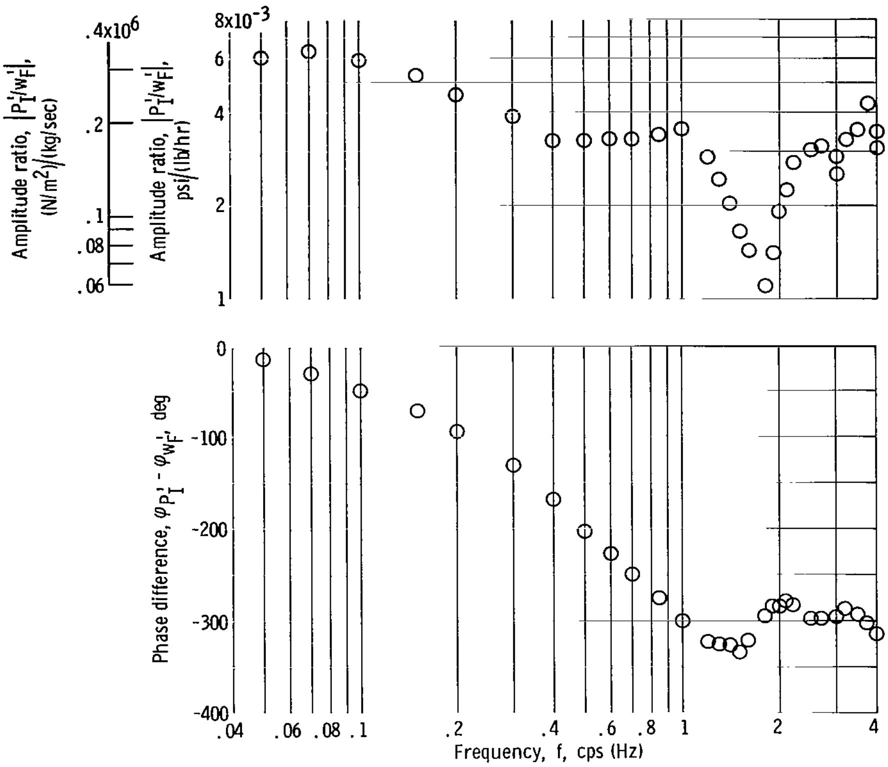
(c) Freon flow rate, 175 pounds per hour (0.022 kg/sec); exit vapor quality, 47 percent; run 9.

Figure 4. - Water temperature as function of length for three different conditions of Freon flow rate. Direction of water flow is to right; direction of Freon flow is to left.



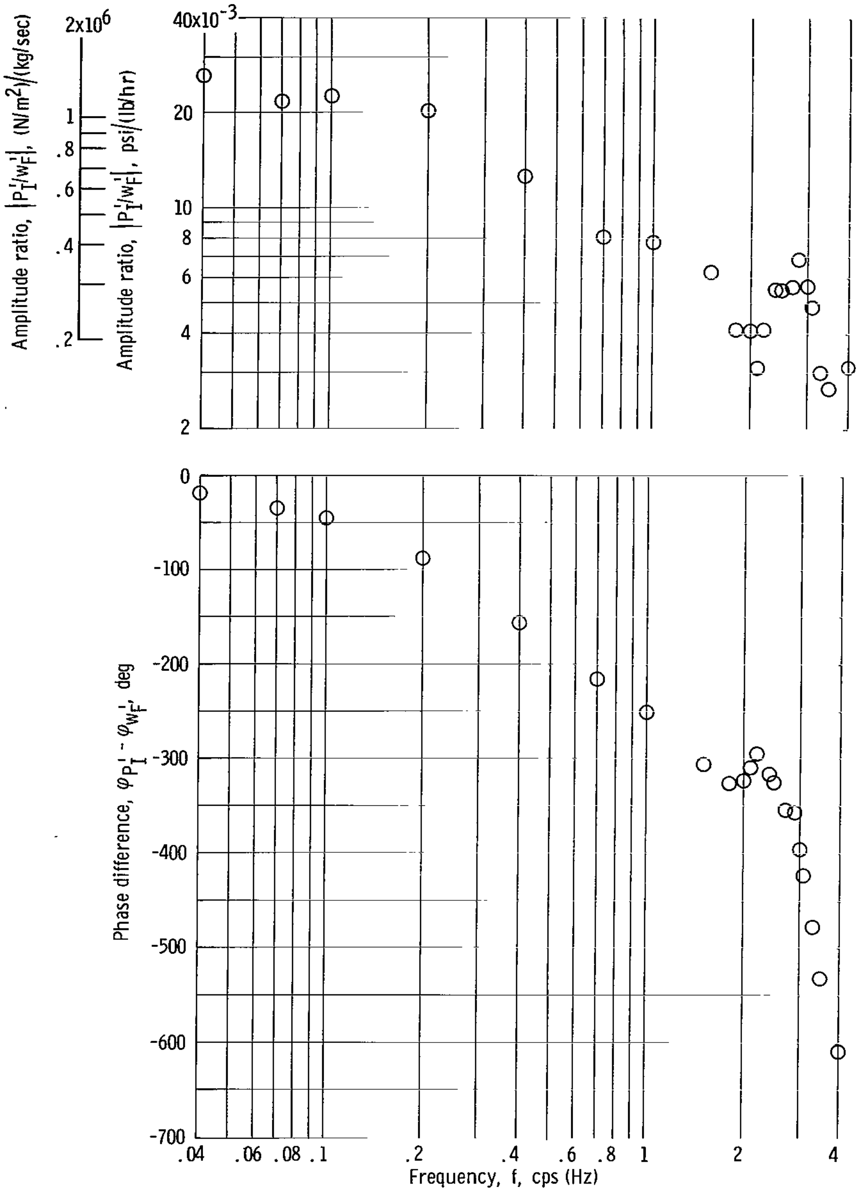
(a) Vapor exit quality, 12 percent; run 1.

Figure 5. - Ratio of boiler inlet pressure perturbation to inlet flow perturbation as function of frequency.



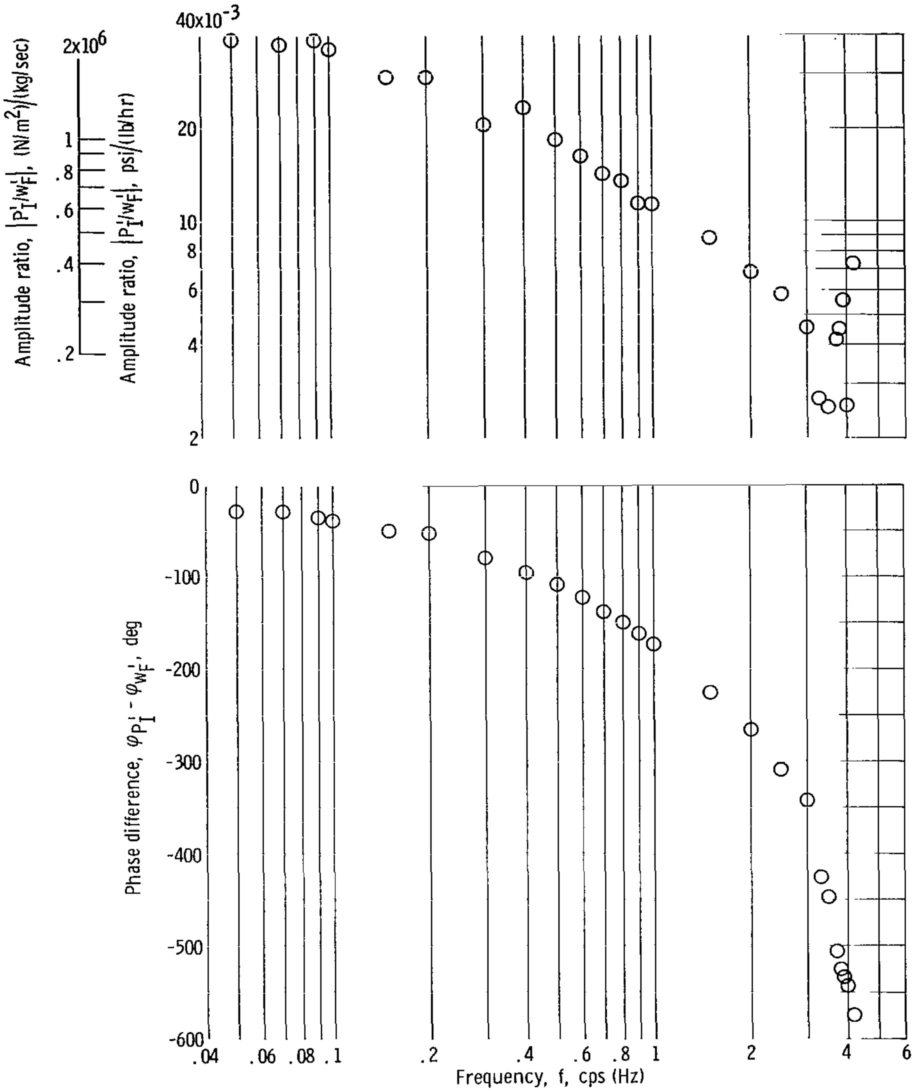
(b) Vapor exit quality, 29 percent; run 3.

Figure 5. - Continued.



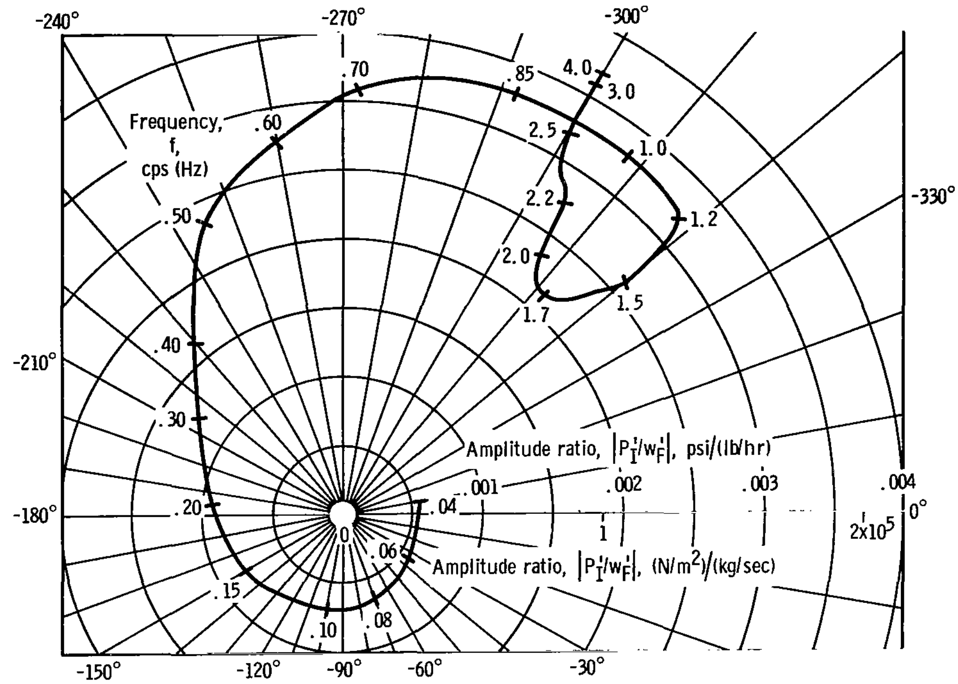
(c) Vapor exit quality, 50 percent; run 4.

Figure 5. - Continued.

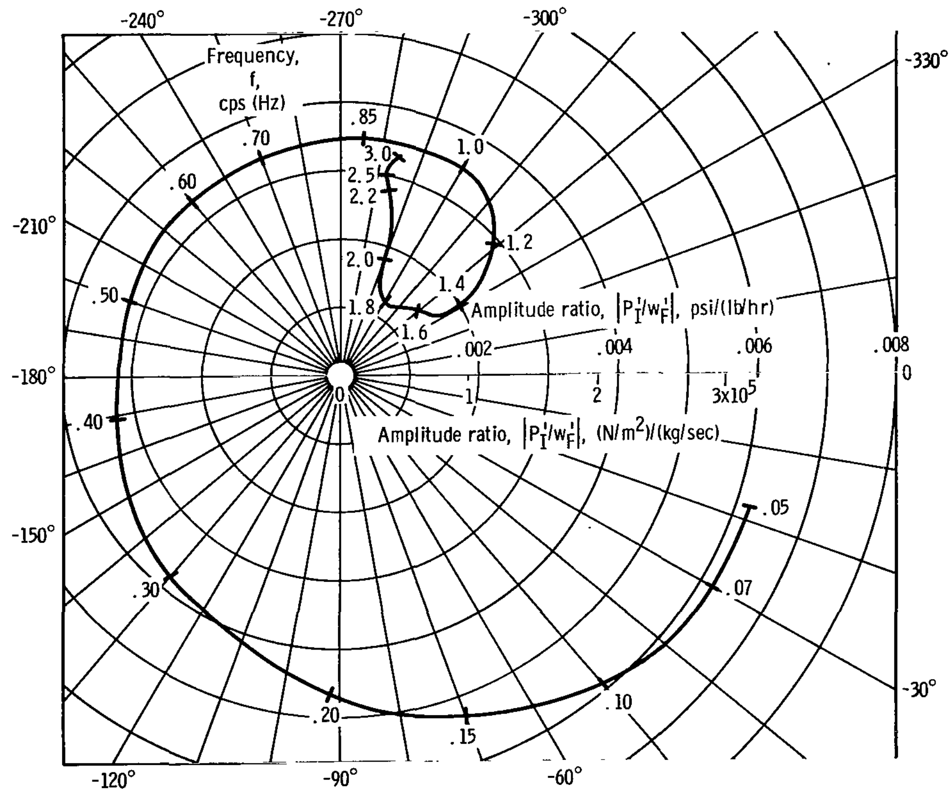


(d) Vapor exit quality, 63 percent; run 5.

Figure 5. - Concluded.

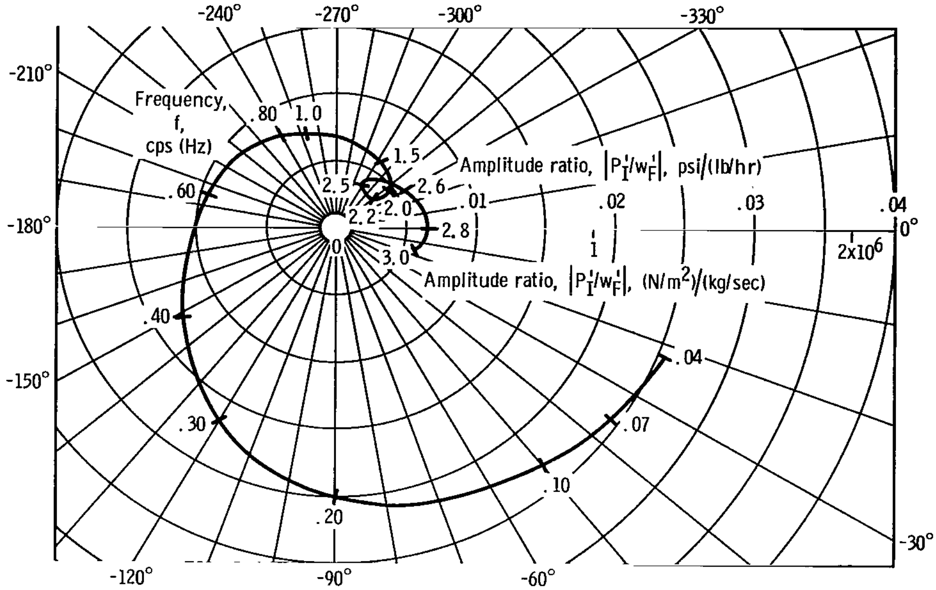


(a) Exit vapor quality, 12 percent; run 1.

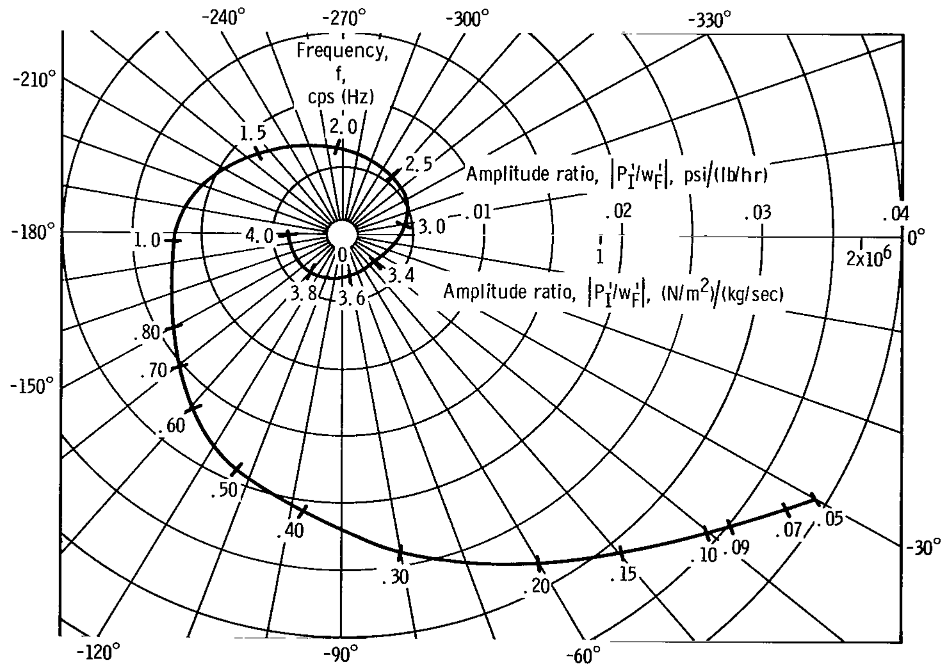


(b) Exit vapor quality, 29 percent; run 3.

Figure 6. - Boiler impedance in polar coordinates.



(c) Exit vapor quality, 50 percent; run 4.



(d) Exit vapor quality, 63 percent; run 5.

Figure 6. - Concluded.

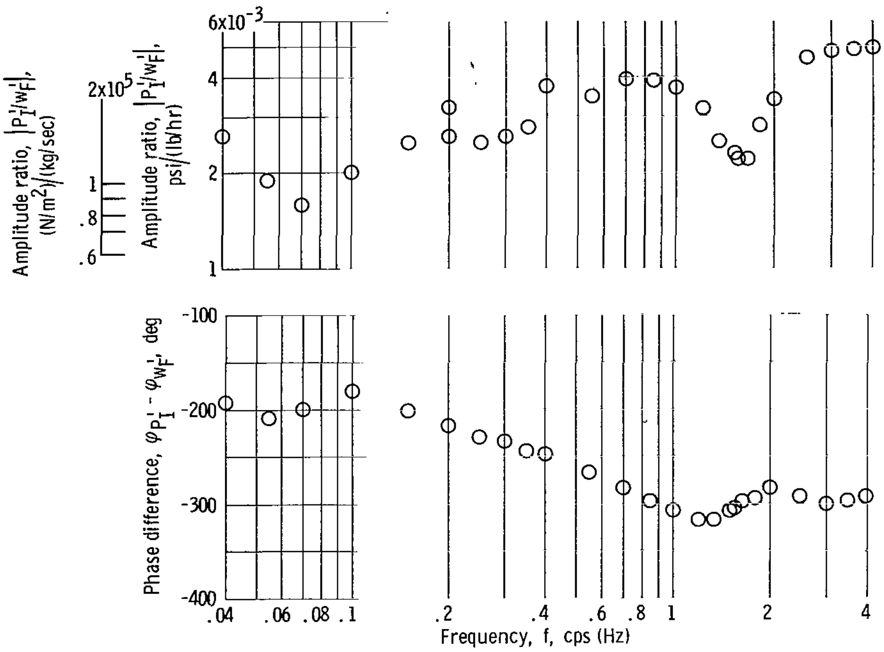


Figure 7. - Pressure and flow perturbation data taken in negative resistance region of boiler. Run 2; Freon flow rate, 656 pounds per hour (0.083 kg/sec); exit vapor quality, 13 percent; inlet water temperature, 211° F (373° K).

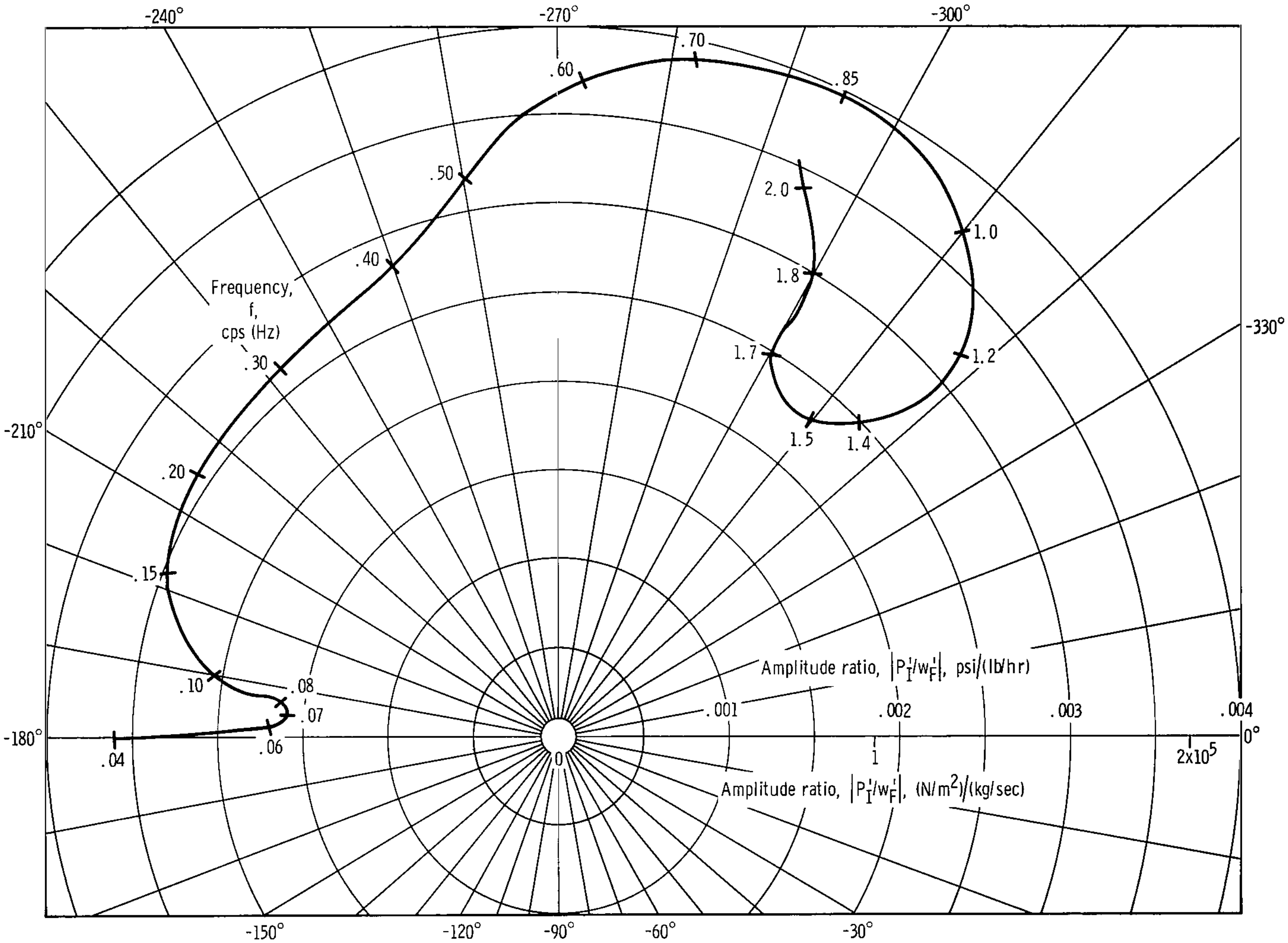


Figure 8. - Boiler impedance for data taken in negative resistance region of boiler. Run 2; Freon flow rate, 656 pounds per hour (0.083 kg/sec); exit vapor quality, 13 percent; water inlet temperature, 211° F (373° C).

NASA-Langley, 1967 — 33 E-3837

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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